

Early Results from TUS, the First Orbital Detector of Extreme Energy Cosmic Rays*

Mikhail Zotov for the Lomonosov–UHECR/TLE Collaboration
*M. V. Lomonosov Moscow State University,
D. V. Skobeltsyn Institute of Nuclear Physics,
Moscow, Russia*

Abstract

TUS is the world’s first orbital detector of extreme energy cosmic rays (EECRs), which operates as a part of the scientific payload of the Lomonosov satellite since May 19, 2016. TUS employs the nocturnal atmosphere of the Earth to register ultraviolet (UV) fluorescence and Cherenkov radiation from extensive air showers generated by EECRs as well as UV radiation from lightning strikes and transient luminous events, micro-meteors and space debris. The first months of its operation in orbit have demonstrated an unexpectedly rich variety of UV radiation in the atmosphere. We briefly review the design of TUS and present a few examples of events recorded in a mode dedicated to registering EECRs.

1 Introduction

Extreme energy cosmic rays (EECRs) with energies $\gtrsim 50$ EeV were discovered more than 50 years ago [1], but their origin and nature still remain unclear, see [2] for the latest review. To a great extent, the problem relates to the very low flux of EECRs. It is sufficient to say that the largest existing experiment, the Pierre Auger Observatory (Auger for short), registered only 146 cosmic rays with energies above 53 EeV in nearly eight years of operation [3]. A smaller Telescope Array (TA) experiment obtained 83 events above 57 EeV in seven years [4]. Another difficulty arises from the fact that neither of the two installations has a full coverage of the celestial sphere.

Both experiments employ a so-called hybrid technique of registering cosmic rays. It includes an array of surface detectors placed on a large area (3000 km² in case of Auger and approximately 700 km² for the TA) and a set of fluorescence telescopes aimed to register ultraviolet (UV) fluorescent and Cherenkov radiation emitted by ionized molecules of nitrogen excited by charged particles of extensive air shower (EAS) cascades generated in the atmosphere by cosmic rays. Another approach aimed to drastically increase the exposure of an experiment was put forward by Benson and Linsley, who suggested to register both kinds of UV radiation emitted during the development of an EAS with an orbital telescope [5, 6]. They estimated that a huge circular field of view about 100 km in diameter, three times larger than the coverage of Auger, was possible with a satellite flying on a circular equatorial orbit at height 500–600 km and equipped with a mirror 36 m in diameter with 10’ resolution and ~ 5000 photomultiplier tubes located at the focal surface of the mirror, at a duty cycle of the order of 20–30%, and the energy threshold below 10 EeV.

While the idea might look simple, one has to overcome a whole number of scientific and technical difficulties to implement it. Despite of a number of efforts, none of the projects was implemented until April 28, 2016, when TUS (Tracking Ultraviolet Set-up), the first orbital detector of EECRs, was launched into orbit from the newly built Vostochny Cosmodrome (Russia) as a part of the scientific payload of the Lomonosov satellite (international designation MVL 300, or 2016-026A). In what follows, I outline the design of TUS and briefly present some of the early results of the on-going analysis of data obtained during the first months of TUS’ operation in orbit.

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2 Design of TUS

The idea by Benson and Linsley attracted attention of physicists in Russia in late 1990s. TUS was first announced in 2001 as a pathfinder for a more advanced KLYPVE mission [7]. Remarkably, John Linsley participated in the project at its early stage. The development was led by the D.V. Skobel'syn Institute of Nuclear Physics at M.V. Lomonosov Moscow State University in collaboration with a number of universities and research organizations in Russia, Korea, and Mexico [8, 9]. TUS inherited the optical scheme of the original design by Benson and Linsley but with modest technical parameters. The instrument consists of a parabolic mirror-concentrator of the Fresnel type and a square-shaped 16×16 -channel photodetector aligned to the focal plane of the mirror. The mirror has an area of about 2 m^2 and a 1.5 m focal distance. Pixels of the photodetector are Hamamatsu R1463 photomultiplier tubes (PMTs) with a 13 mm diameter multialkali cathode. The pixels are grouped in 16 identical photodetector modules. Light guides with square entrance apertures and circular outputs are employed to uniformly fill the focal surface. All PMTs have black blends extending 1 cm above their light guides as a kind of protection against side illumination. A 2.5 mm thick UV filter is placed in front of each PMT cathode to limit the measured wavelength to the 300–400 nm range. The field of view (FOV) of TUS equals $\pm 4.5^\circ$, which results in an area of approximately $80 \text{ km} \times 80 \text{ km}$ at sea level so that a single channel observes a $5 \text{ km} \times 5 \text{ km}$ square [10]. (The Lomonosov satellite has a sun-synchronous orbit with an inclination of 97.3° , a period of $\approx 94 \text{ min}$, and a height of about 470–500 km.)

TUS can operate in four modes with different time sampling windows (“time frames”). The main mode is aimed at registering EASs and has a time sampling window of $0.8 \mu\text{s}$. Time frames of $25.6 \mu\text{s}$ and 0.4 ms are utilized for studying transient luminous events (TLEs) of different kinds, and a window of 6.6 ms is available for detecting micro-meteors and possibly space debris. A data record of any TUS event includes 256 discrete waveforms, one for each channel, and every waveform contains analog-to-digital converter (ADC) counts for 256 time frames. Due to certain limitations of the Lomonosov hardware, all parameters of the trigger system are adjusted so that the trigger rate does not exceed approximately one event per minute. All four modes of operation were tested since the launch.

Recall that the situation with the energy spectrum of cosmic rays above $\sim 50 \text{ EeV}$ was unclear at the time the TUS project was put forward. In particular, it was suggested by the Haverah Park [11] and AGASA [12] experiments that there was no cut-off of the spectrum at energies predicted by Greisen, Zatsepin and Kuz'min [13, 14]. It was estimated based on the AGASA data that TUS would be able to register about 20 events with energies above 200 EeV and $\simeq 900$ events above 20 EeV in three years of operation [7]. It became clear that these expectations were too optimistic as soon as HiRes and Auger found that the flux of cosmic rays was strongly suppressed at energies $\gtrsim 50 \text{ EeV}$ [15, 16]. Currently, the main scientific objective of TUS in relation to cosmic rays is to test the technique of observing EECRs from space and to obtain data on the UV background of nocturnal atmosphere to be used in the development of the future missions such as KLYPVE (K-EUSO) [17] and JEM-EUSO [18].

Still, there are chances that TUS registers a number of EECRs. Various simulations were performed for TUS before the launch, and the energy threshold for effective registering of EECRs was determined to be approximately 70 EeV , so that the instrument should be able to register several events above the threshold in 5 years of continuous operation assuming the energy spectrum obtained with Auger for highly inclined EAS [19]. In what follows, we only discuss results obtained in the EAS mode. A few examples of data recorded in the TLE and meteor modes can be found in [20, 21].

3 Selected Results

3.1 Instant Track-like Flashes

The biggest surprise of the first days of the TUS operation in orbit were multiple strong flashes growing in a single time frame ($0.8 \mu\text{s}$, i.e., instantly in the TUS time scale) simultaneously in

a number of adjacent PMTs usually producing linear tracks in the focal surface. Due to these features, they are tentatively called “instant track-like flashes.” An example of such an event is shown in Fig. 1. Notice one of the pixels is saturated reaching the maximum possible ADC count of 1023, which approximately corresponds to 2000 photons at the PMT pupil in conditions of a low background flux. The situation is typical for this kind of flashes, see other examples in [20, 21, 22]. The length and shape of tracks produced in the focal surface vary from one event to another but we have not found any correlation of them with time of observation or position of Lomonosov yet, though waveforms demonstrate some specific features on certain days. Total intensity of the flashes also varies with the number of saturated pixels exceeding eight in some cases. The flashes constitute 12% of nearly 25 thousand events recorded in the EAS mode from May 19 till December 16, 2016. Their geographic distribution has two distinct maxima at latitudes 35°S – 50°S and 45°N – 60°N and a minimum at 0° – 15°N . This is drastically different from the distribution of the whole data set, which is approximately uniform in latitudes 50°S – 70°N .

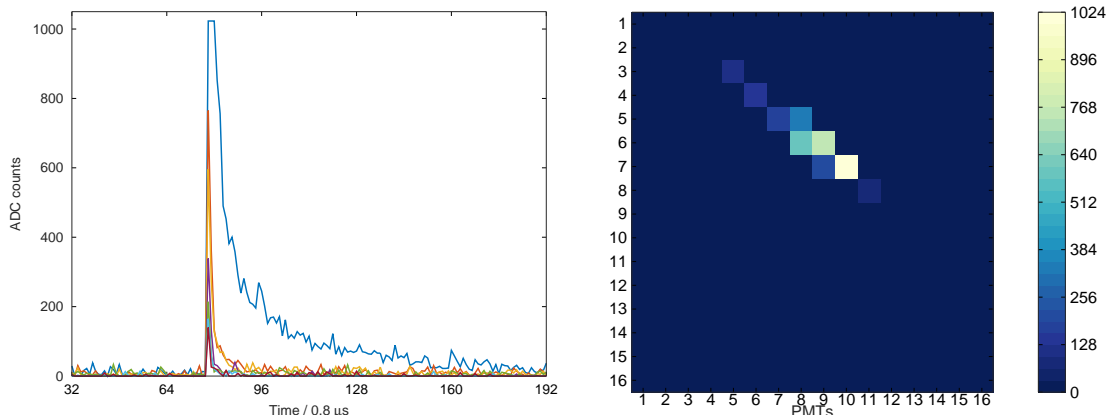


Figure 1: Example of an instant track-like flash. Left: waveforms of a few PMTs with the highest ADC counts. Colours denote waveforms of different PMTs. Right: snapshot of the focal surface at the moment of the maximum signal. Here and below, colours denote ADC counts.

The instant track-like flashes cannot result from extensive air showers generated by EECRs in the atmosphere because a nearly horizontal EAS should produce a track composed of adjacent pixels that flash throughout approximately 16 consecutive time frames, not all at once. Simulations performed using the Geant4 software toolkit [23] have revealed that protons with energies from 100–200 MeV up to a few GeV that hit and penetrate the UV filters nearly parallel can produce UV radiation, and result in tracks similar to those recorded by TUS [22]. On the other hand, weak flashes with low ADC counts and only one or a few pixels involved are potentially originated from electrons of the inner radiation belt. Other possible sources of this kind of events are also being considered.

According to other simulations, Cherenkov light, either reflected from Earth or generated within the mirror medium by an upward-going particle can also potentially generate instant flashes with a spot produced in the focal plane [24, 25]. The probability of this kind of events is small, but its importance calls for a dedicated analysis.

3.2 Flashes Related to Thunderstorms

Another interesting group of events consists of spatially extended flashes with ADC counts that monotonically increase (up to random fluctuations of the signal) during $\gtrsim 60 \mu\text{s}$ as shown in the left panel of Fig. 2. We tentatively call them “slow flashes” to distinguish from the events discussed in the previous section. A slow flash typically evolves simultaneously across the focal surface, producing its nearly uniform illumination. In most cases, ADC counts continue growing until the end of a record but sometimes a maximum is reached and the signal begins vanishing before the record is

complete. In a few cases, illumination of the focal plane by a slow flash is strongly non-uniform, as demonstrated in the right panel of Fig. 2.

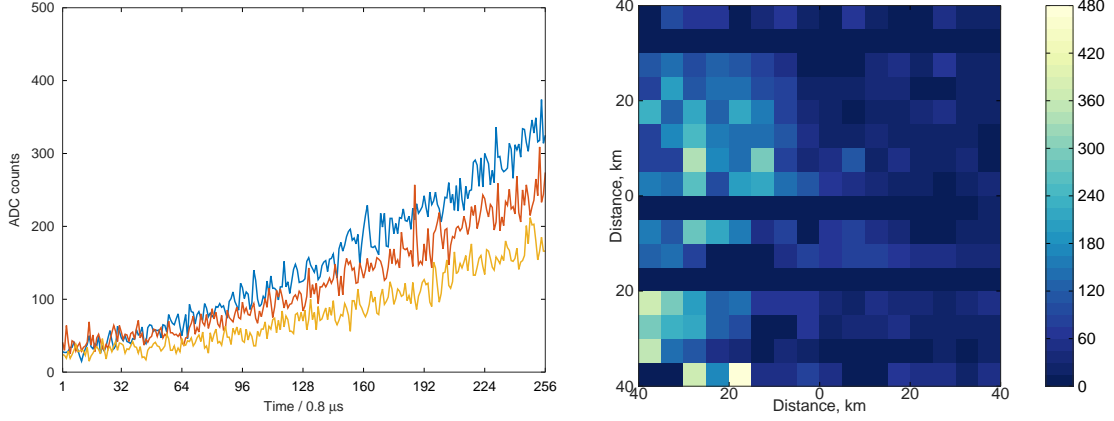


Figure 2: Example of a slow flash registered on September 12, 2016, at 04:20:09 UTC. The centre of the FOV was at $21^{\circ}8\text{N}$, $74^{\circ}5\text{W}$. Left: waveforms of three PMTs. Right: snapshot of the focal plane at the maximum of the flash. Here and below, numbers to the left and beneath snapshots indicate approximate distances from the centre of the FOV at ground level; geographic North is at 11° – 12° counterclockwise from the top of the focal plane, East is respectively to the right. Rows with zero ADC counts are due to malfunctioning PMT modules.

An analysis of the geographic distribution of slow flashes demonstrated its correlation with known regions of high lightning flash rates. This provided a clue to a possible origin of this kind of events. A sample of slow flashes registered from August 16, 2016, to September 19, 2016, was compared with data from the World-Wide Lightning Location Network (WWLLN). We analysed data at distances up to ~ 2000 km from the TUS FOV, which corresponds to the maximum distance from which a ray of light tangent to the Earth is visible from the Lomonosov orbit. It was found that for the time window of ± 1 s, which matches the accuracy of the TUS trigger time stamps, the majority of “companion” lightnings were registered at distances 400–1600 km from positions of the respective flashes recorded by TUS. It is likely that the origin of slow flashes uniformly illuminating the focal surface is diffusive light of distant lightning strikes scattered by the surface of the TUS mirror. In contrast to this situation, a lightning strike was registered by the WWLLN 0.37 s prior to the TUS trigger in around 85 km South-West from the centre of the FOV resulting in non-uniform illumination of the focal plane shown in Fig. 2.

A few other kinds of events registered with TUS are related to thunderstorm activity and TLEs, among them so-called elves [26]. Elves are short-lived optical events that manifest at the lower edge of the ionosphere as bright rings expanding at the speed of light up to a maximum radius of ~ 300 km. Up to December 16, 2016, five events registered with TUS in the EAS mode have been identified as elves. The first of them is shown in Fig. 3. The event was registered on September 7, 2016, at 09:51:35 UTC over the Pacific Ocean ($11^{\circ}62\text{S}$, $161^{\circ}68\text{W}$). It appeared as a bright arc crossing the focal plane from North-West to South-East, fading steadily. A lightning strike within 0.6 s was registered by the WWLLN at a distance of about 180 km North-West from the centre of the TUS field of view. The position of the lightning, the form of the bright arc in the focal plane, and the temporal evolution of the waveforms strongly support the conjecture that this was an elfe. Another example of an elfe registered with TUS can be found in [21].

3.3 Events with noise-like waveforms

In the majority of events registered by far with TUS ($> 80\%$), waveforms look like a stationary stochastic process with ADC counts fluctuating around some average values that mostly depend on

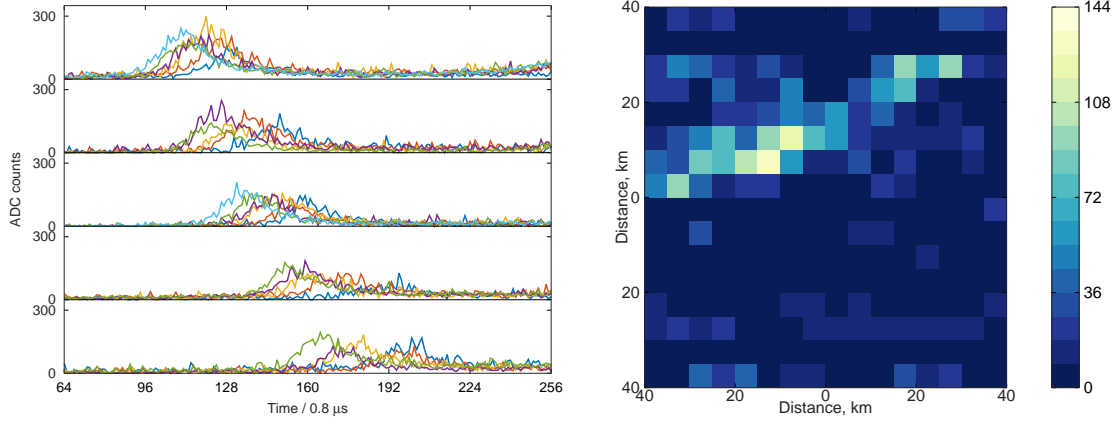


Figure 3: Event recorded over the Pacific Ocean on September 7, 2016. Left: waveforms of the brightest pixels of the PMT modules shown as rows 3–7 from the top of the snapshot. Bottom: a snapshot of the focal plane for time frame number 176. The bright arc started in the top NW corner of the focal plane and moved towards the SE corner with its brightness decreasing.

conditions of observations. Illumination of the focal surface is typically uniform up to sensitivity of individual PMTs during moonless nights and far from urban regions. Trigger of such events seems to be caused by random fluctuations of the nocturnal UV background radiation.

Illumination of the focal plane becomes strongly non-uniform during moonlit nights because TUS does not have side shields, and moonlight can arrive directly at the focal surface. Other sources of non-uniform illumination are auroral ovals, thunderstorm regions and industrial sites, urban regions and generally objects related to human activities. Fig. 4 presents examples of events recorded near Nagoya (September 28, 2016, at 14:22:47 UTC, centre of the FOV at 35°1N, 136°9E) and Buenos Aires (November 18, 2016, 02:43:49 UTC, 34°7S, 58°9W). TUS routinely registers numerous events of this kind, especially in regions with clear atmosphere, but in most cases a concrete source of the bright signal cannot be identified because of the insufficient spatial resolution of the instrument. A clear frequency modulation at 100 Hz or 120 Hz is observed above cities when TUS operates in the TLE mode with the time window of 0.4 ms, see an example in [20]. Interestingly, it was found that some existing artificial sources (not related to the experiment) can mimic strength and spatio-temporal dynamics of signals expected from extensive air showers generated by EECRs.

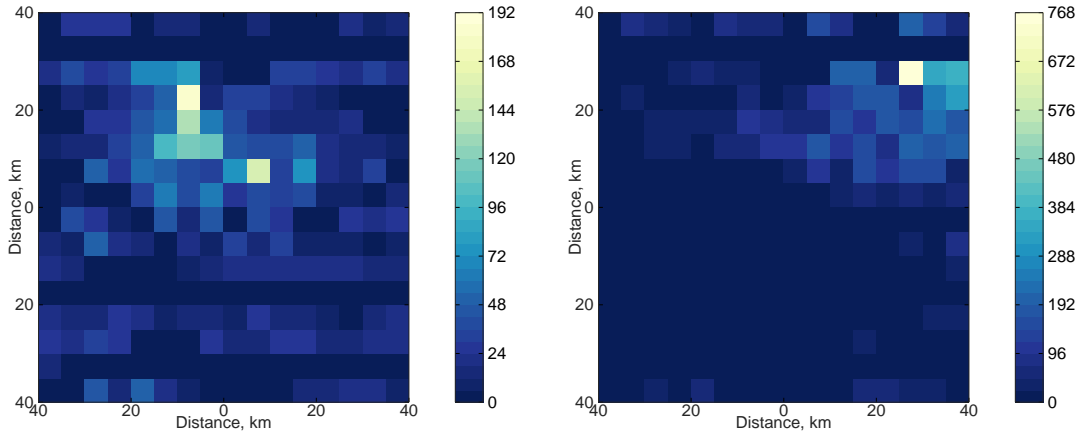


Figure 4: Examples of snapshots of the focal plane made above cities. Left: Nagoya, Japan, in cloudy weather conditions. Right: Buenos Aires, Argentina, in clear weather.

There are also TUS events that do not fit in the above three groups. Some of them form their own small subgroups, others are unique thus far. An example of a violent flash registered by TUS on September 5, 2016, near Sardinia, for which we have failed to identify an anthropogenic or a natural source can be found in the slides of the talk [27]. At the time of writing, unusual events are undergoing analysis and will be reported elsewhere.

4 Conclusions

TUS is the first orbital detector capable of registering fast UV flashes in the nocturnal atmosphere of the Earth in the imaging mode, providing much more detailed data than the earlier Tatiana, Tatiana-2 and Vernov missions of Lomonosov Moscow State University [28, 29, 30]. The results already obtained are mostly unexpected and provide important information about the nocturnal UV background necessary for successful development of the future KLYPVE (K-EUSO) and JEM-EUSO missions. TUS has also demonstrated that an orbital detector can be utilized for simultaneously studying processes that manifest themselves with UV flashes in the atmosphere but have inherently different nature and time scales. Still, following the main objective of the experiment, much efforts are being put in the search for EAS candidates in the data. A number of methods employed resulted in selecting a few promising events. Their detailed analysis is in progress, and its results will be presented in a dedicated report.

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The Lomonosov–UHECR/TLE collaboration

S.V. Biktemerova^b, A.A. Botvinko^c, N.P. Chirsakaya^a, V.E. Ereemeev^a, G.K. Garipov^a, V.M. Grebenyuk^{b,d}, A.A. Grinyuk^a, S. Jeong^f, N.N. Kalmykov^a, M.A. Kaznacheeva^a, B.A. Khrenov^a, M. Kim^f, P.A. Klimov^a, M.V. Lavrova^a, J. Lee^f, O. Martinez^g, M.I. Panasyuk^a, I.H. Park^f, V.L. Petrov^a, E. Ponce^g, A.E. Puchkov^c, H. Salazar^g, O.A. Saprykin^c, A.N. Senkovsky^c, S.A. Sharakin^a, A.V. Shirokov^a, A.V. Tkachenko^b, L.G. Tkachev^{b,d}, I.V. Yashin^a, M.Yu. Zotov^a

^aM.V. Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow, 119991, Russia

^bJoint Institute for Nuclear Research, Joliot-Curie, 6, Dubna, Moscow region, Russia, 141980

^cSpace Regatta Consortium, ul. Lenina, 4a, 141070 Korolev, Moscow region, Russia

^dDubna State University, University str., 19, Bld.1, Dubna, Moscow region, Russia

^eDepartment of Physics and ISTS, Sungkyunkwan University, Seobu-ro 2066, Suwon, 440-746 Korea

^fBenemérita Universidad Autónoma de Puebla, 4 sur 104 Centro Histórico C.P. 72000, Puebla, Mexico